

# Global Simulation of Electromagnetic Ion Cyclotron Waves

George V. Khazanov<sup>1</sup>

**K. V. Gamayunov<sup>1</sup>, J. U. Kozyra<sup>2</sup>, and D. L. Gallagher<sup>1</sup>**

*<sup>1</sup>NASA Marshall Space Flight Center*

*<sup>2</sup>Space Physics Research Laboratory, University of Michigan*

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# Synopsis

- Is bouncing EMIC wave concept valid?
- What EMIC wave data show?
- How to model EMIC wave spectral properties?
- Why do we need self-consistent RC and EMIC waves model?
- What is new in our new global EMIC waves simulation studies?
- Summary



# Is Bouncing Wave Concept Valid?

1. It is well known that geomagnetic pulsations observed on the ground in the band Pc 1-2 (0.1-5 Hz) are generated in the equatorial magnetosphere (as EMIC waves) via RC and cold plasmasphere interaction.
2. Amplitude-time records of EMIC waves observed on the ground show a series of wave packets which alternate between hemispheres. Based on the signatures of frequency-time dynamic spectra of Pc 1-2, wave packets bounced between two hemispheres was accepted as a propagation mechanism of EMIC waves since 1960s [*Saito, 1969*].
3. In situ observation of EMIC waves by *Erlandson et al.* [1990, 1992] and *Fraser et al.* [1996] showed only propagation of these waves away from the equator. Mix propagation of EMIC waves have been seen in a data reported by *Loto'aniu et al.* [2005] and *Engebretson et al.* [2007].
4. More recent ground observations have also questioned the bouncing wave concept and suggested modulation of ion-cyclotron instability by long-period (Pc3/4) pulsations [*Mursula et al.*, 1997].
5. The association between EMIC wave signatures on the ground and magnetosphere is difficult to interpret due to two primary complications: (a) magnetospheric heavy composition, and (b) phenomenon of ionospheric ducting.



# Why Bouncing Wave Concept Should Be Valid?

1. There are two types of instabilities in plasma: the absolute instability and the convective one [*Sturrock*, 1958]. The absolute instability is not realized in the case of Pc 1 [*Troitskaya and Guglielmi*, 1967; *Gomberoff and Neira*, 1983; & *Guglielmi et al.*, 2001].
2. That means the excitation of Pc 1 (as well as EMIC waves) is impossible without reflection of the waves from the ionosphere or from some turning points in the magnetosphere. This also means that locally the magnetosphere is only an amplifier and not the generator of Pc 1 signals. Therefore the amplified signal has to be returned into the system for the positive feedback [*Guglielmi et al.*, 2001], and in such an event the magnetosphere may switch over to a generation regime (Global Instability [*Lifshitz and Pitaevsky*, 1979]).
3. Depending on the heavy ion magnetospheric content ( $\text{He}^+$ , and  $\text{O}^+$ ), reflecting boundaries of the EMIC waves are placed in the magnetosphere and not in the ionosphere. This leads to the formation of an open ion cyclotron resonator in the equatorial zone of the magnetosphere with eigenmodes in the Pc 1 frequency band [*Guglielmi et al.*, 2001]. The time-dependent IC wave packet, which can be presented as a superposition of these eigenmodes, oscillates about the equator with the period of a typical Pc 1 repetition period.

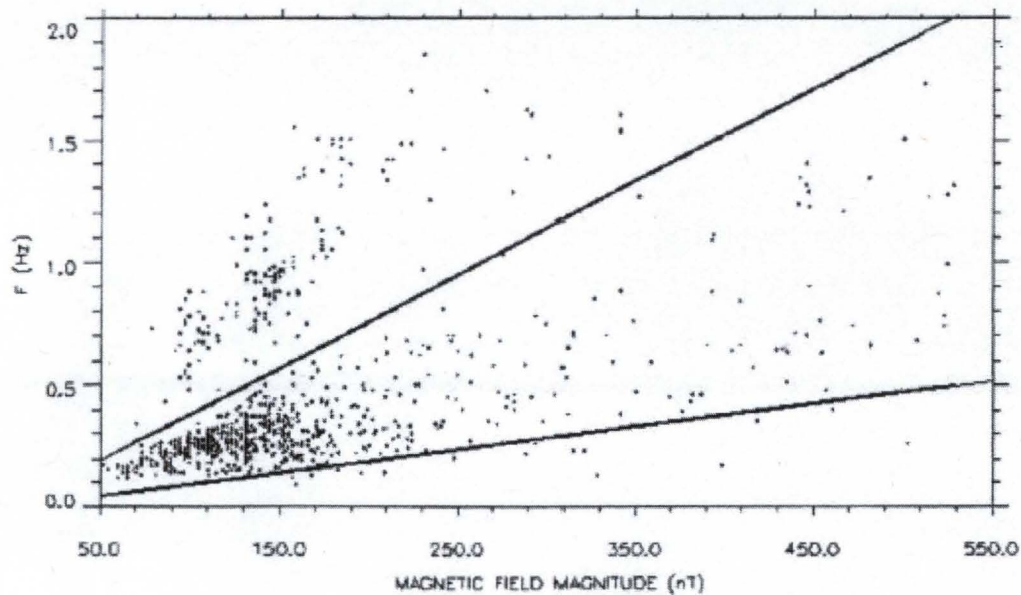
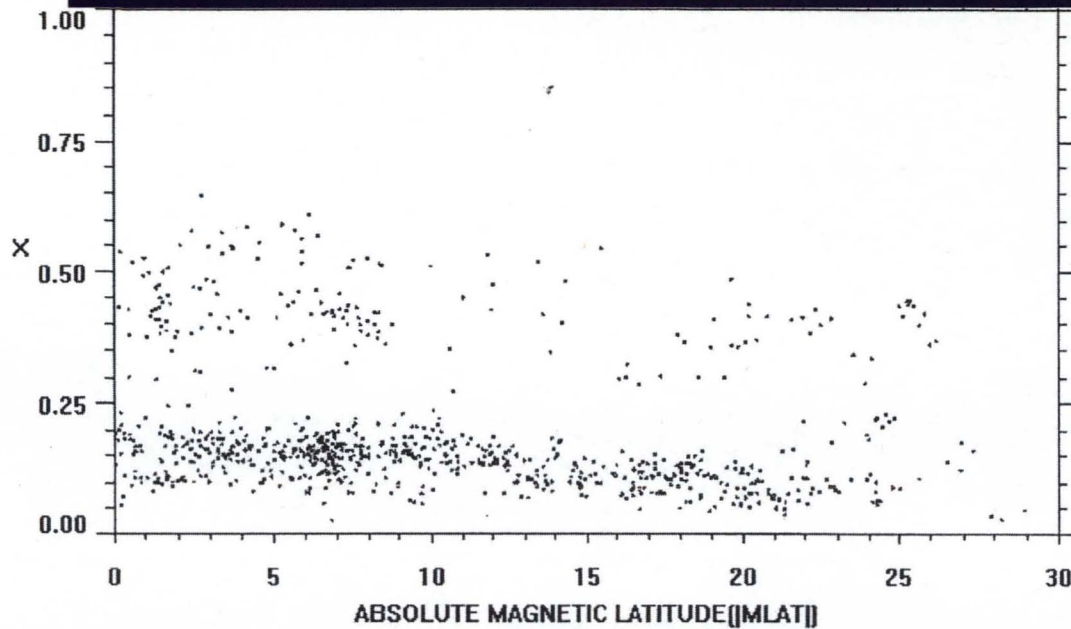


# EMIC Wave Observations

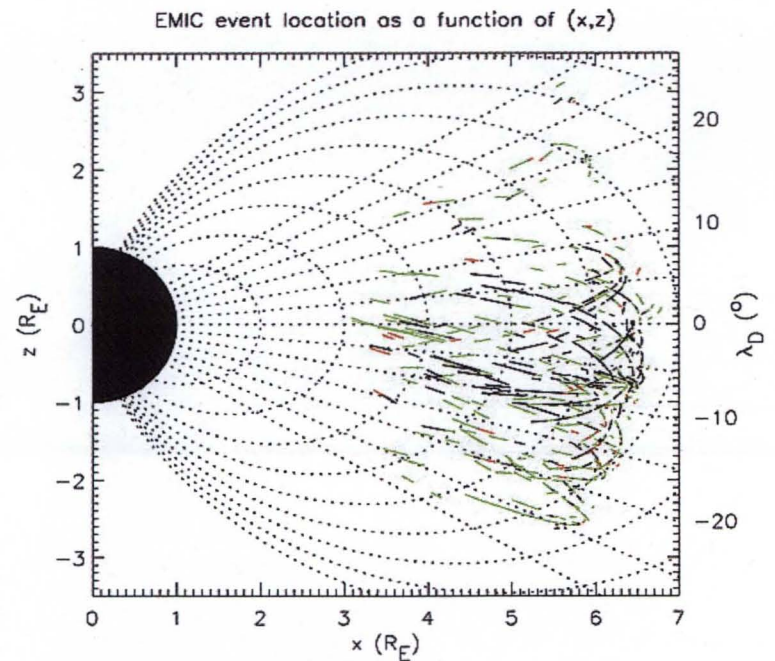
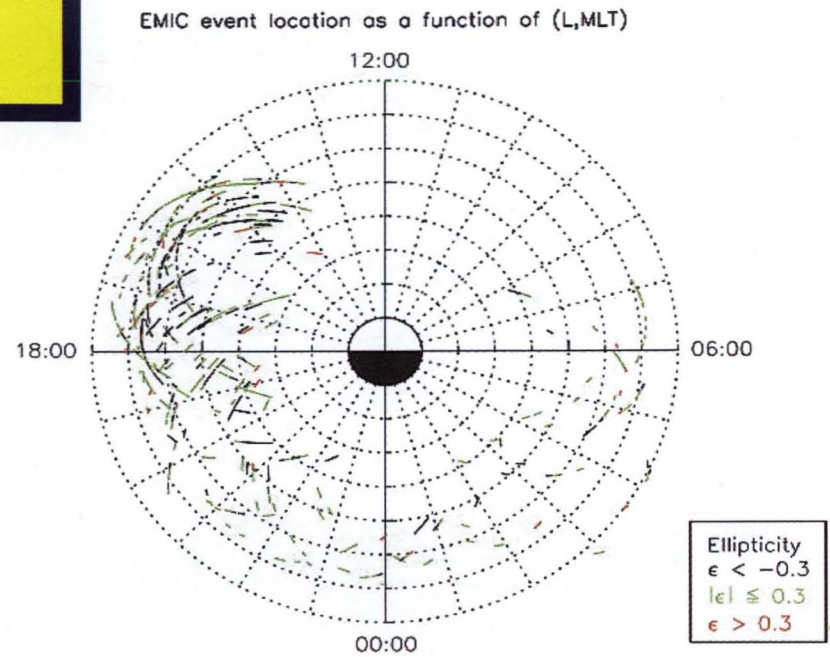
1. Using FFT analysis, *Fraser* [1985] and *Ishida et al.* [1987] reported that the minimum variance polar angle is generally less than 30deg. Assuming that the observed waves could be represented by a single plane mode, they related the derived angle to wave normal angle as  $\theta_{kB} = \theta_{\min}$ .
2. *Anderson et al.* [1996] found that polarization parameters vary over a time period of a few wave periods, and significant polarization axis fluctuations are a common feature of EMIC waves in magnetosphere. He developed a minimum variance technique which operates on timescales of a few wave periods (wave step technique). *Anderson et al.* [1996] showed that the FFT analysis can yield dramatic underestimation of  $\theta_{\min}$  (more than 45deg) and overestimation of ellipticity. Using the wave step technique, they found a significant number of wave intervals with  $\theta_{\min} > 70\text{deg}$  (AMPTE/CCE).
3. *Denton et al.* [1996] found that the observed polarization properties are inconsistent with the assumption that the resultant waves are from a single plane wave, and presented quantitative analysis of the effects of superposition on the observed wave polarization properties. They found ellipticity=0.07, and  $\theta_{kB} = 77\text{deg}$  for the 1985-018 EMIC wave event (AMPTE/CCE).



# CRRES Observations



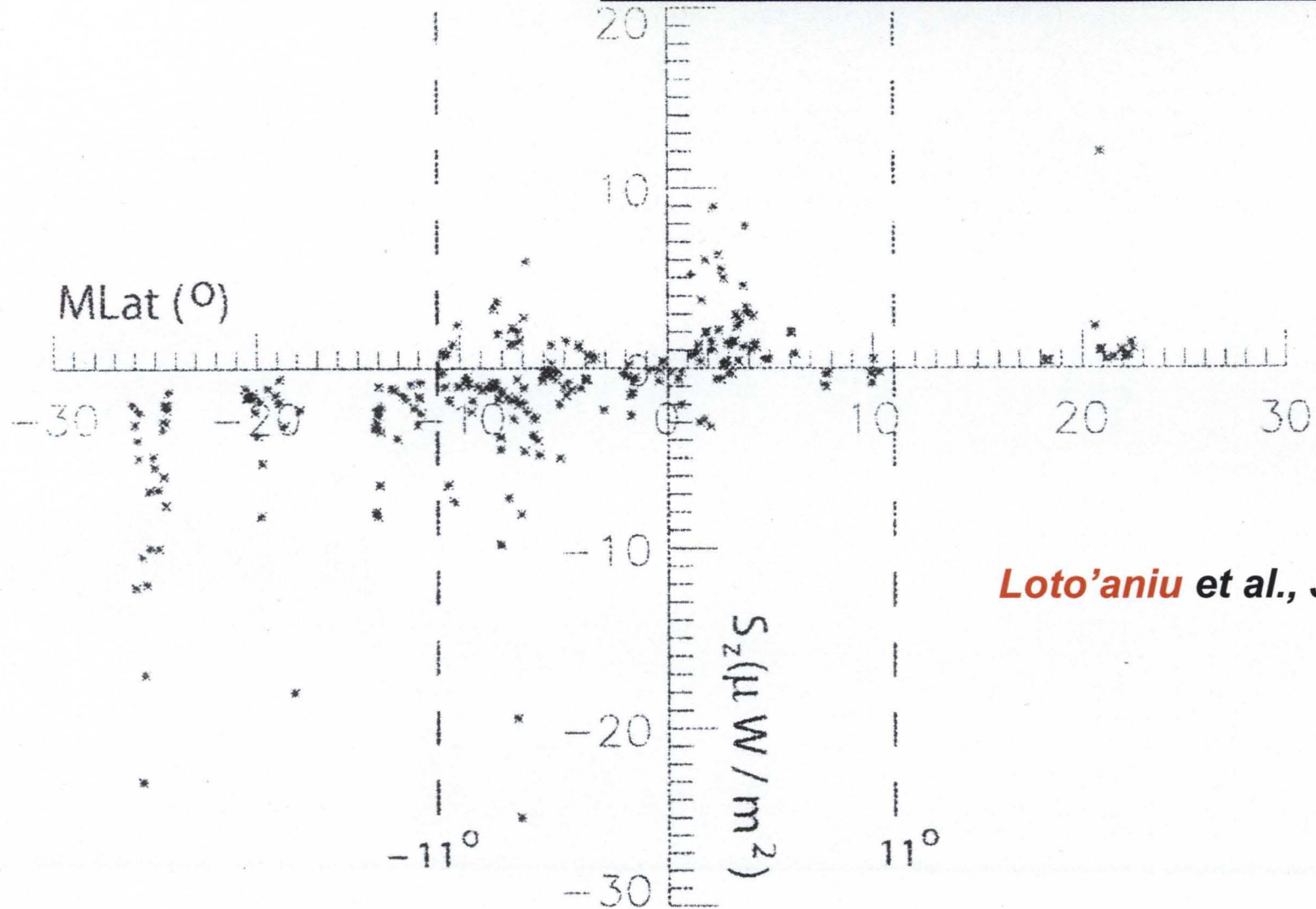
*Fraser & Nguyen*, JASTP, 2001



*Meredith et al.*, JGR, 2003



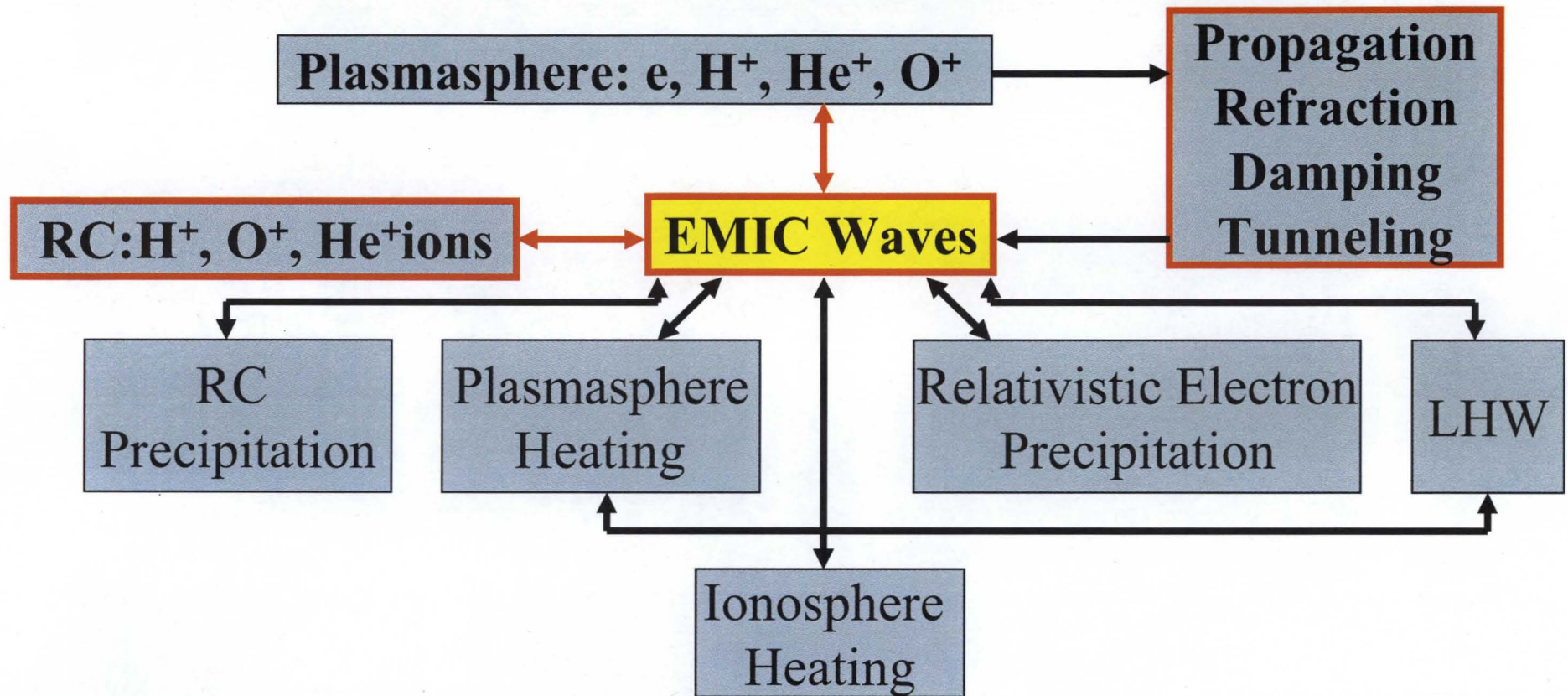
# CRRES Observations



*Loto'aniu et al.*, JGR, 2005

*Engbreton et al.* [2005, 2007] (Cluster and Polar) found a similar EMIC wave energy propagation dependence but with mixed direction within approximately Mlat +/- 20 deg, and consistently toward the ionosphere for higher magnetic latitudes.

# How to Model EMIC Wave Spectral Properties?



## New RC/EMIC Waves Modeling Features

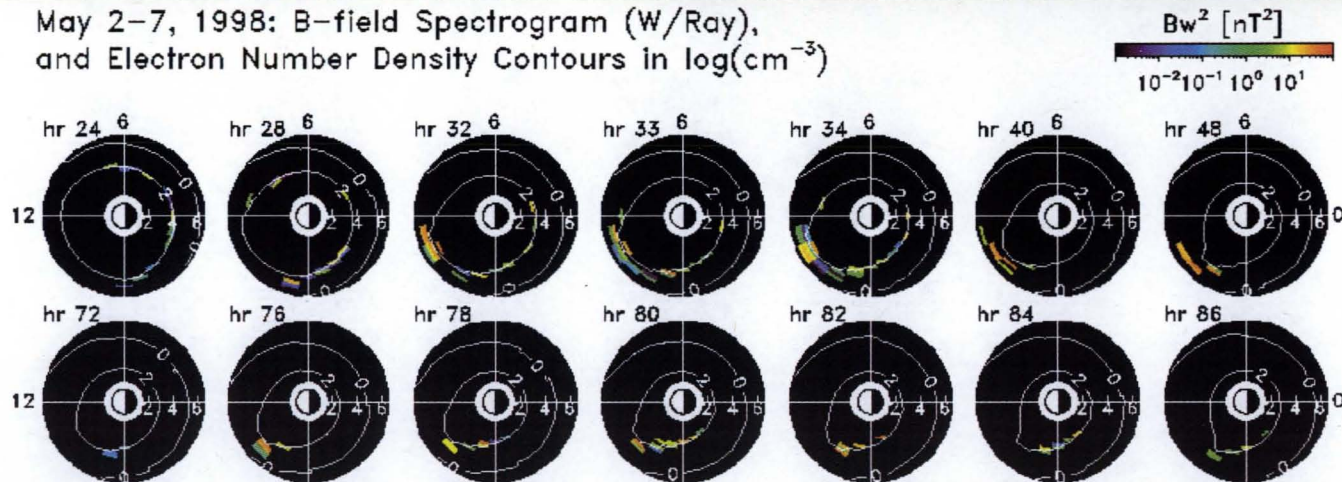
- Explicit SC solutions for RC PD and EMIC wave PSD
- **Explicit wave propagation/refraction modeling**
- No assumptions regarding the shapes of PD and wave PSD



# EMIC Waves and RC Precipitations

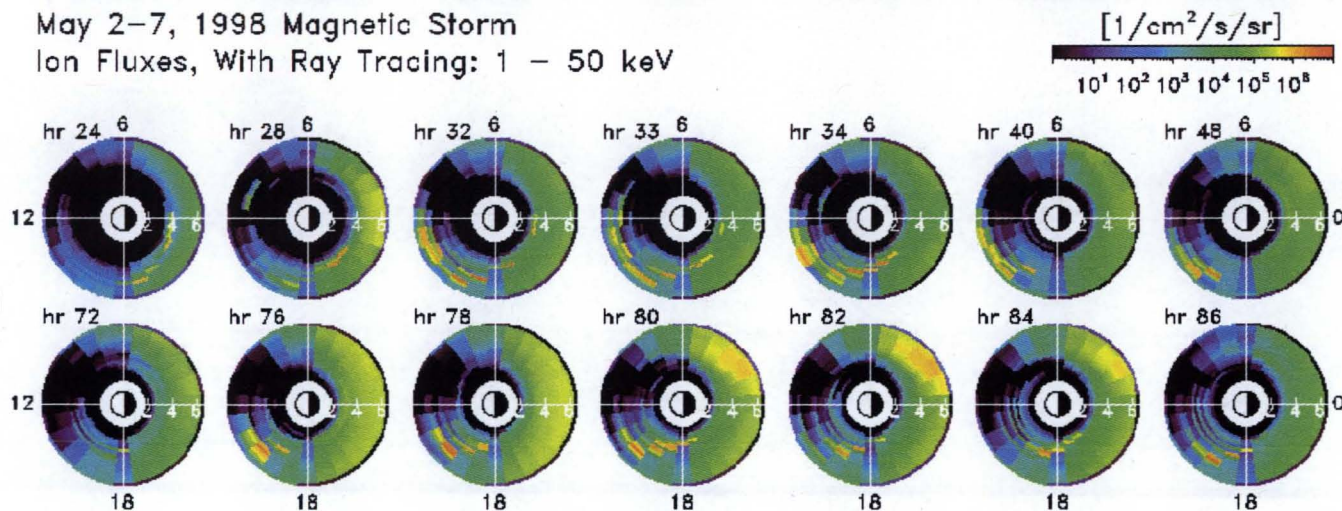
May 2–7, 1998: B-field Spectrogram (W/Ray),  
and Electron Number Density Contours in  $\log(\text{cm}^{-3})$

Wave  
Power



May 2–7, 1998 Magnetic Storm  
Ion Fluxes, With Ray Tracing: 1 – 50 keV

Precipitation

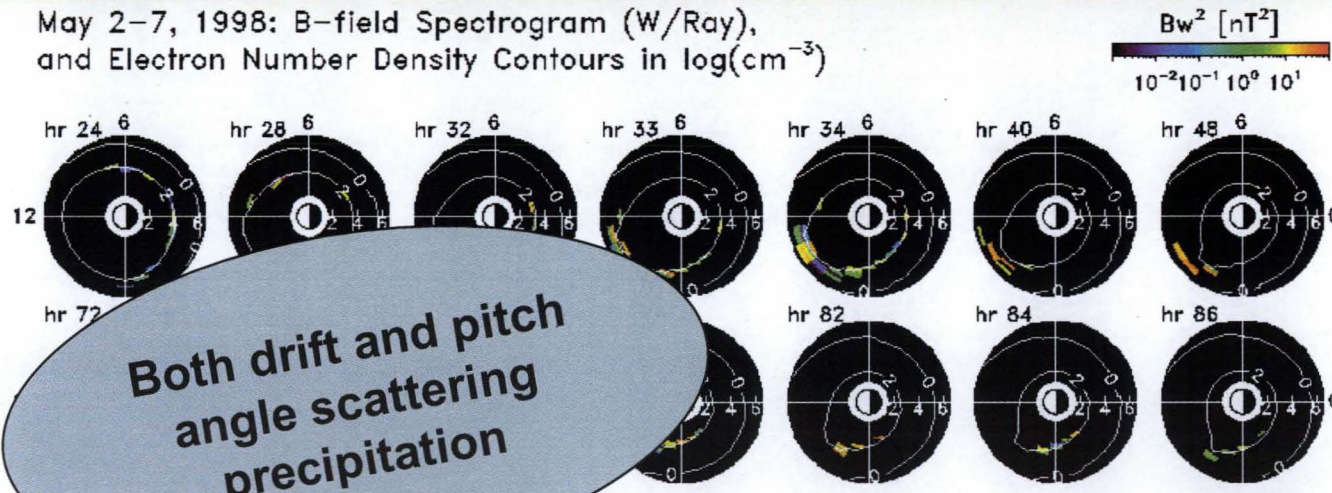




# EMIC Waves and RC Precipitations

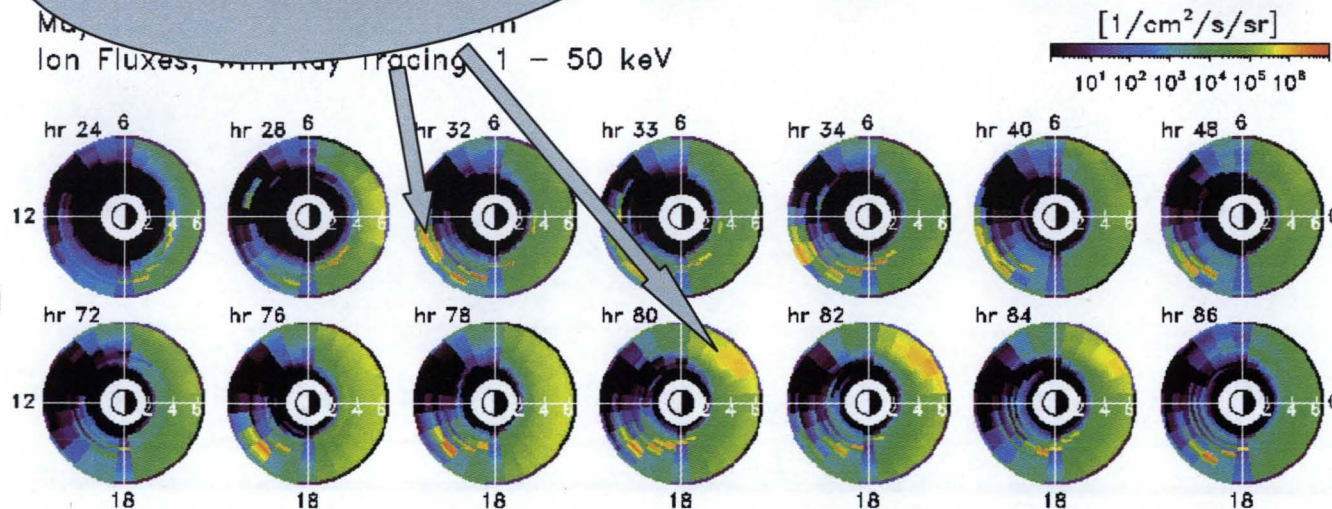
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Wave  
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Ion Fluxes, W/Ray Tracing 1 – 50 keV

Precipitation

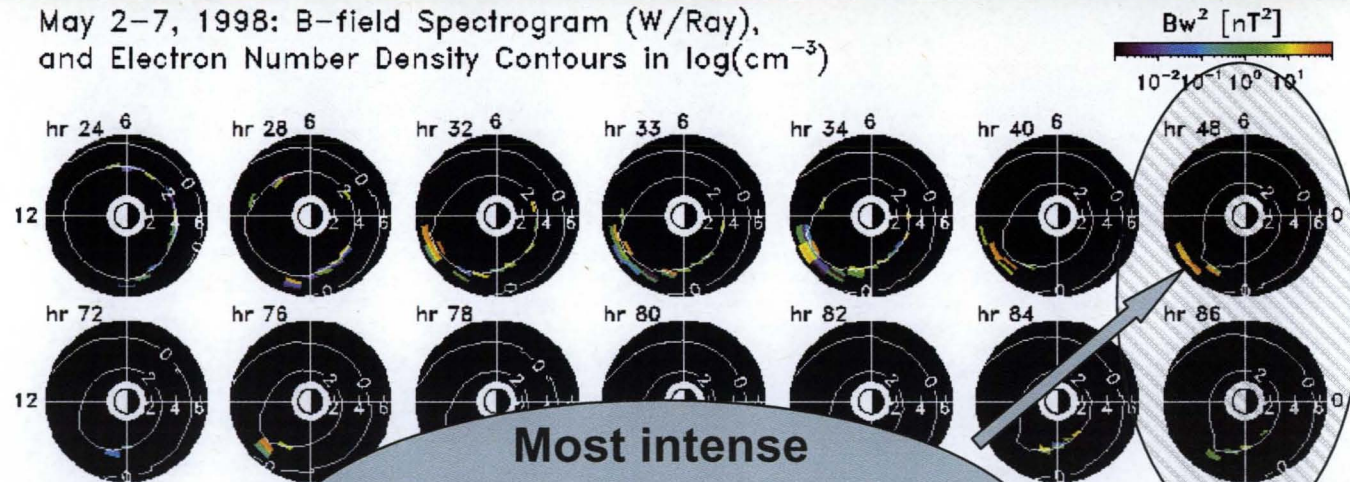




# EMIC Waves and RC Precipitations

May 2–7, 1998: B-field Spectrogram (W/Ray),  
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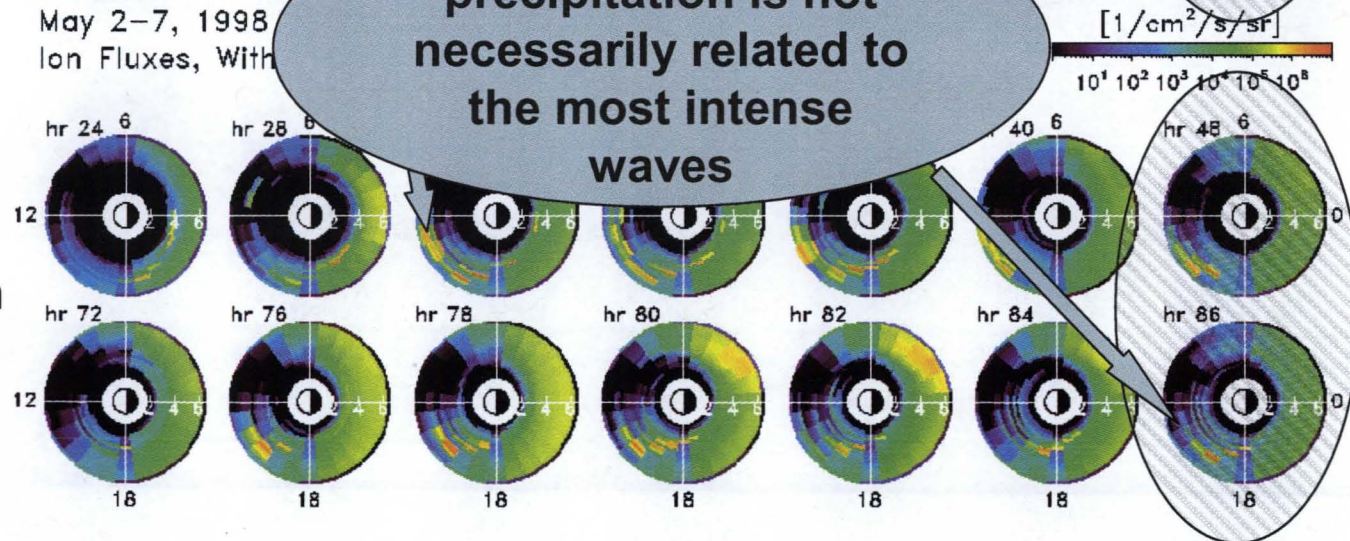
Wave  
Power



Most intense  
precipitation is not  
necessarily related to  
the most intense  
waves

May 2–7, 1998  
Ion Fluxes, With

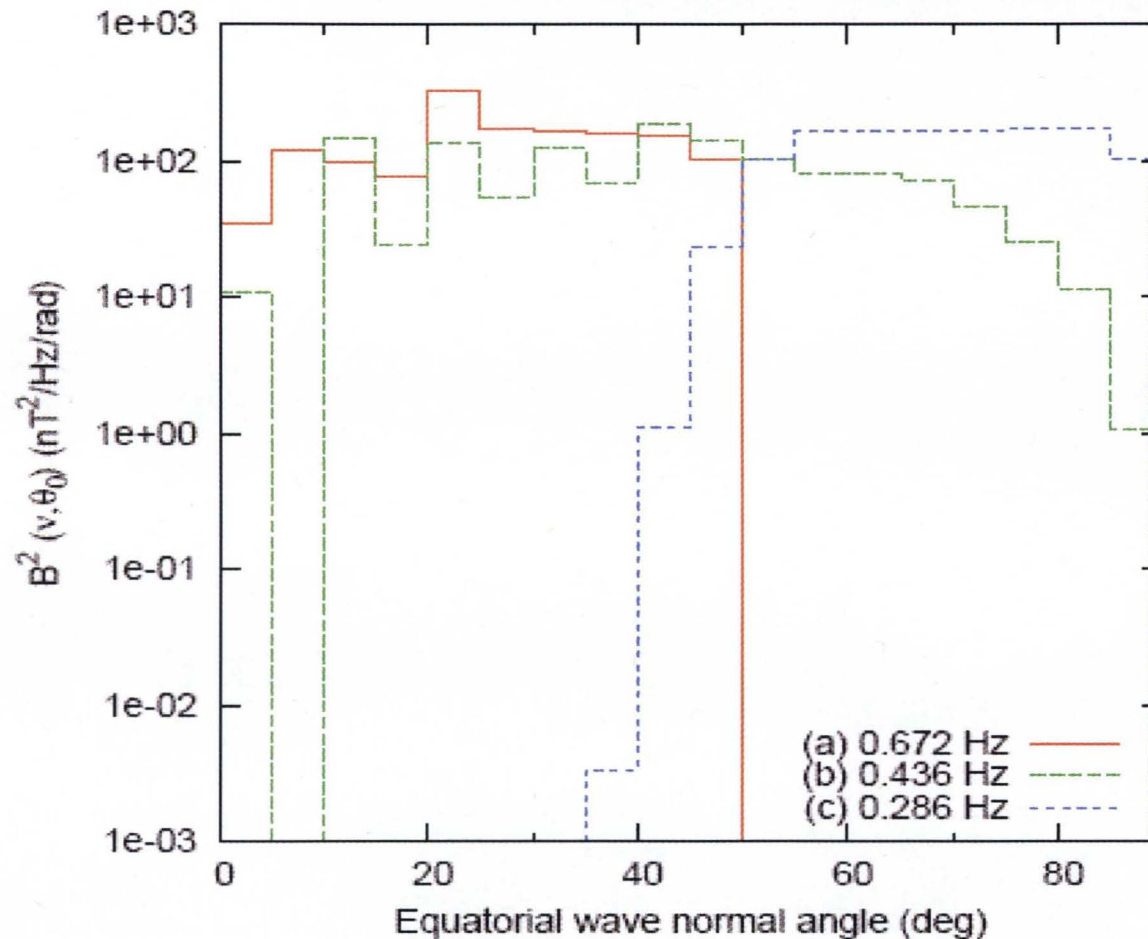
Precipitation



$$UT = 48, MLT = 14, B^2 = 16.3 \gamma^2, F = 1.4 \cdot 10^5 (\text{cm}^2 \text{s ster})^{-1}$$

$$UT = 86, MLT = 16, B^2 = 2.7 \gamma^2, F = 3.5 \cdot 10^6 (\text{cm}^2 \text{s ster})^{-1}$$

# Equatorial PSD for $\text{He}^+$ -mode EMIC Waves



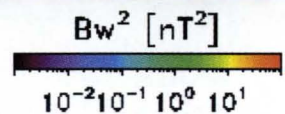
**All the squared magnetic field spectra are obtained at 48 hours after 0000 UT on 1 May, 1998. (a)  $L=5.25$ ,  $MLT=16$ , (b)  $L=5.75$ ,  $MLT=15$ , and (c)  $L=5.75$ ,  $MLT=14$  [Khazanov et al., 2006].**

Only one model is capable to do this job. Convective growth rate is incapable to do this.



# EMIC Waves and Electron Heating

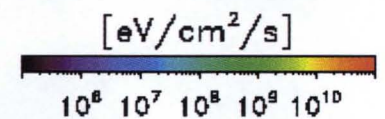
May 2–7, 1998: B-field Spectrogram (W/Ray),  
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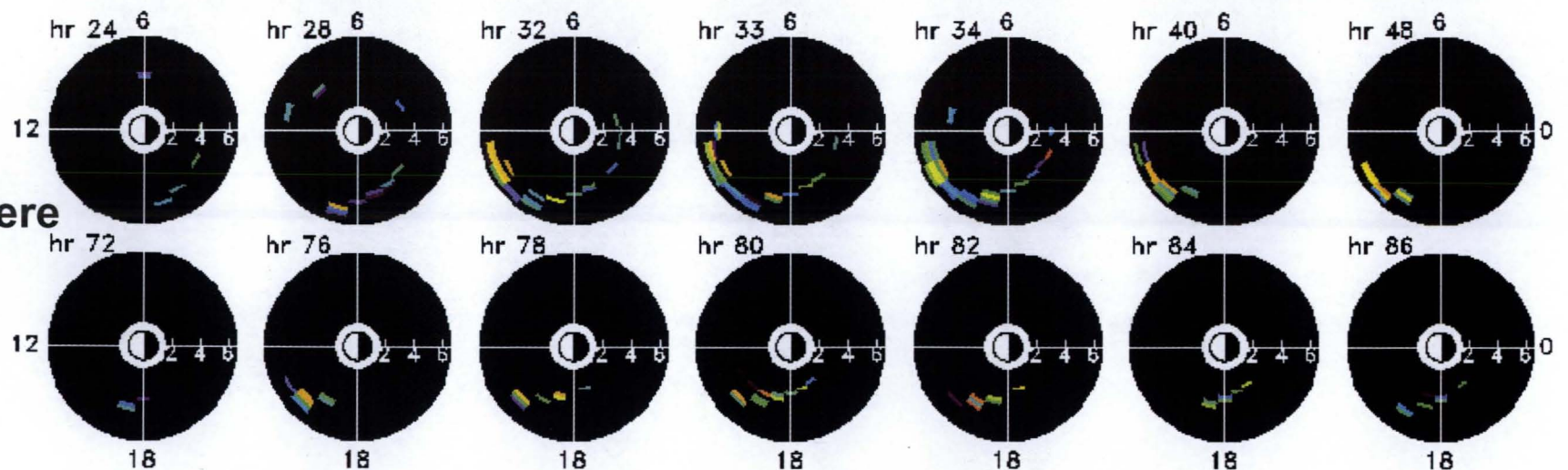
Wave  
Power



May 2–7, 1998 Magnetic Storm  
Electron Thermal Fluxes due to EMIC Waves



Ionosphere  
Heating

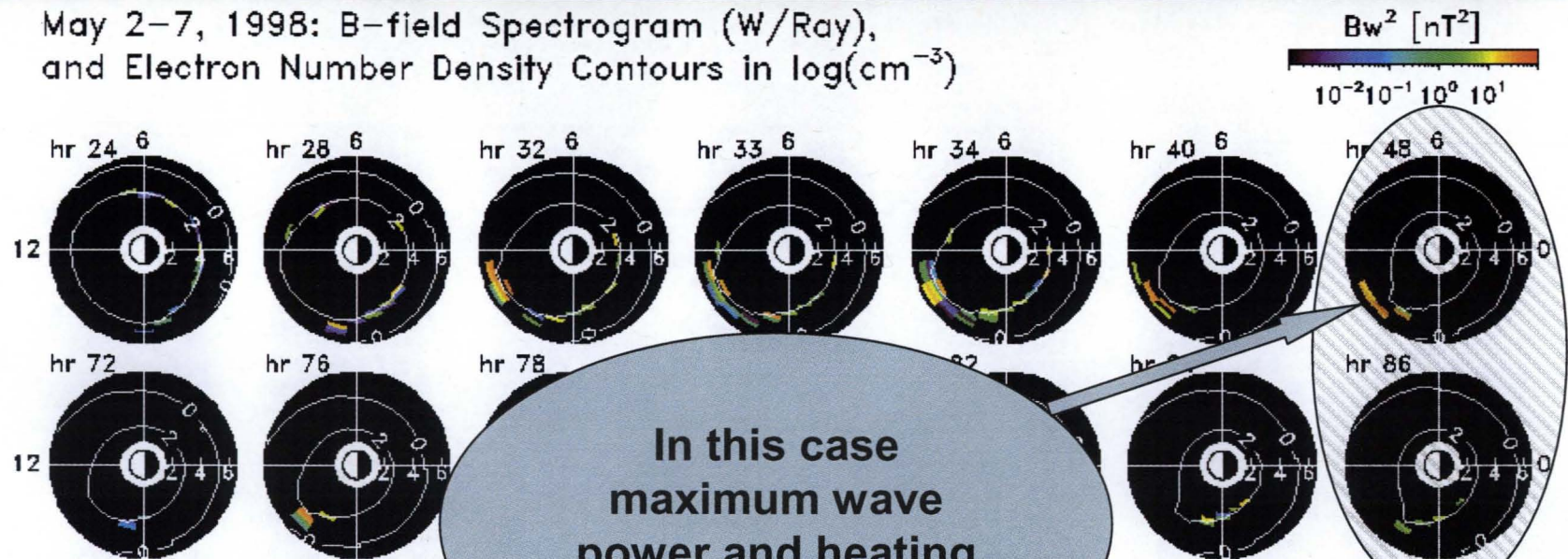




# EMIC Waves and Electron Heating

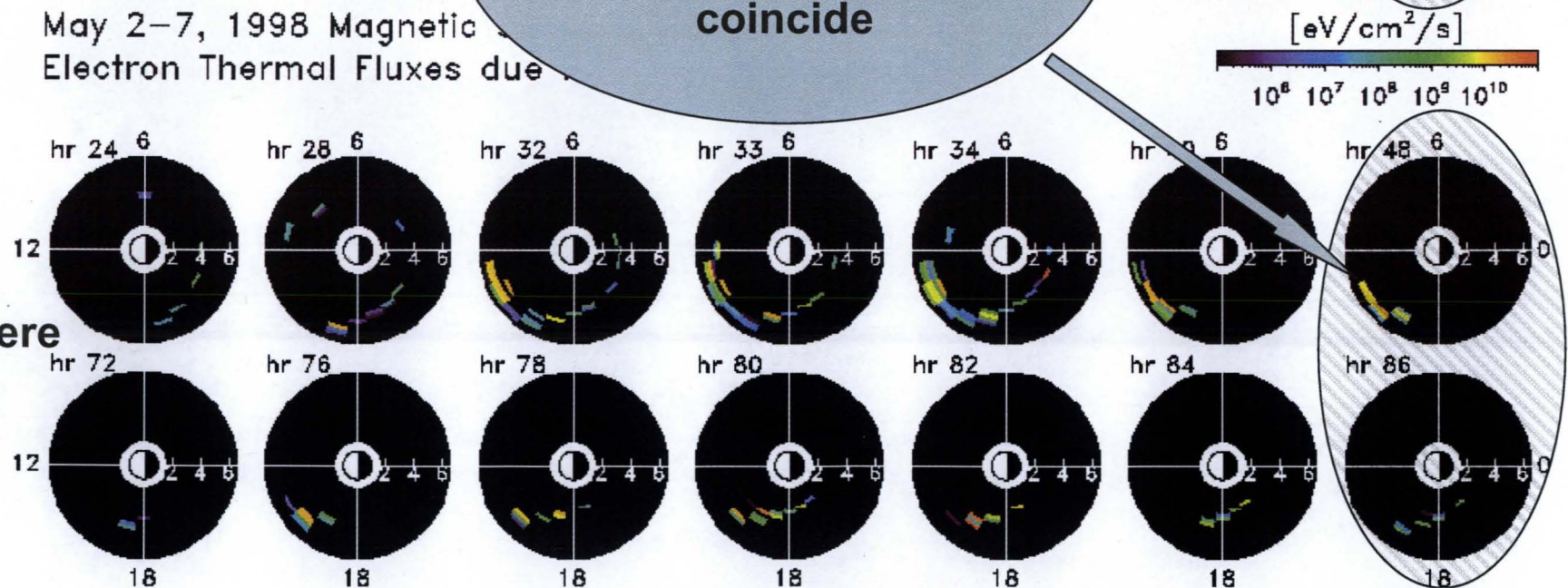
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Wave  
Power



May 2–7, 1998 Magnetic  
Electron Thermal Fluxes due

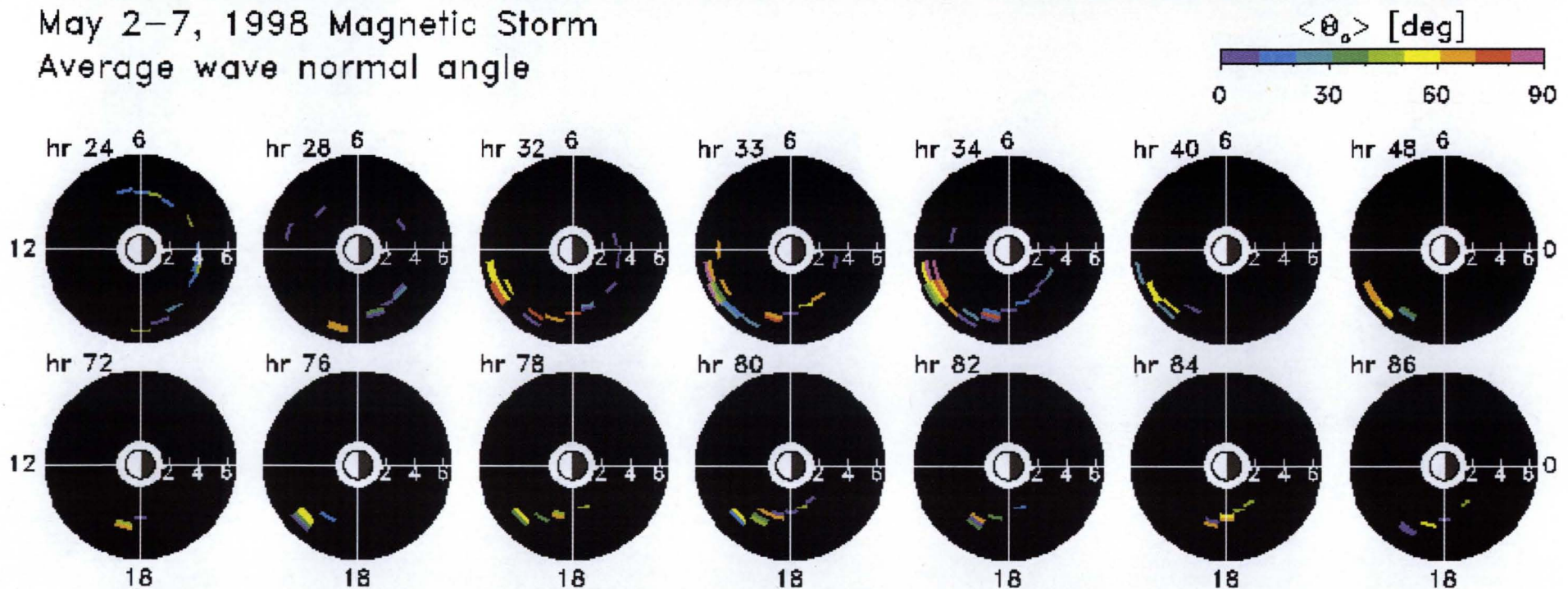
Ionosphere  
Heating





# Average Equatorial WNA for He<sup>+</sup>-mode

May 2–7, 1998 Magnetic Storm  
Average wave normal angle



The EMIC wave normal angle distributions are highly variable both in space and time, and the equatorial distributions range from a field-aligned distribution to a highly oblique distribution. The occurrences of the oblique and field-aligned wave normal angle distributions appear to be near the same during the May 1998 storm with a slight dominance of the former events.



# Examine Pitch-Angle Diffusion Dependence on EMIC WNA Distribution

Assume

$$B^2(\omega) \approx \exp\left\{-\frac{(\omega - \omega_m)^2}{\delta\omega^2}\right\}, \omega_{LC} \leq \omega \leq \omega_{UC},$$

$$\omega_{LC} = \omega_m - \delta\omega, \omega_{UC} = \omega_m + \delta\omega, \omega_m = 3\Omega_{O^+}, \delta\omega = 0.5\Omega_{O^+}$$

$$\text{Case A : } 0^\circ \leq \theta \leq 30^\circ, 150^\circ \leq \theta \leq 180^\circ$$

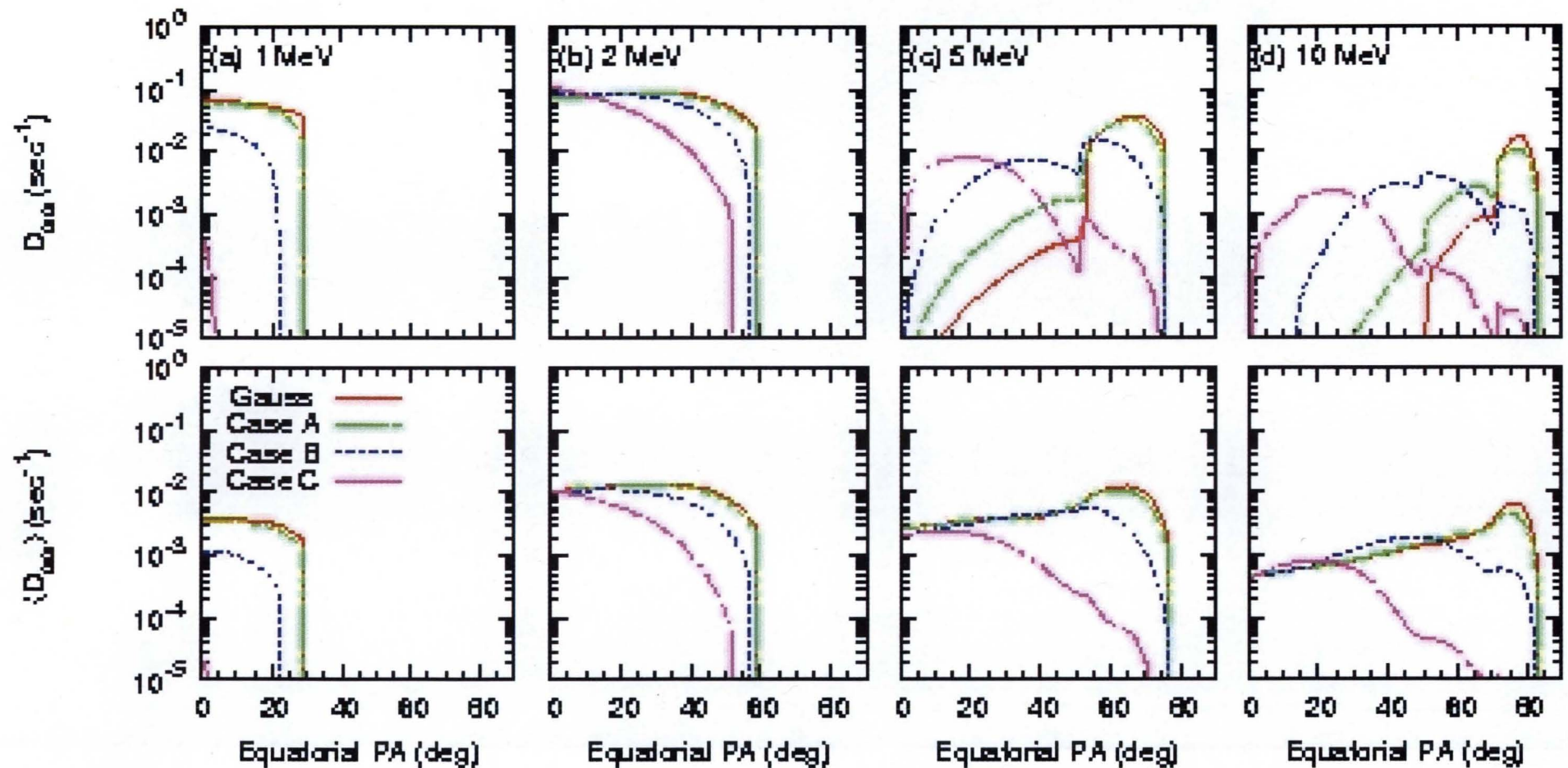
$$\text{Case B : } 30^\circ \leq \theta \leq 60^\circ, 120^\circ \leq \theta \leq 150^\circ$$

$$\text{Case C : } 60^\circ \leq \theta \leq 89^\circ, 91^\circ \leq \theta \leq 120^\circ$$

$$\iint B^2(\omega, \theta) d\omega d\theta = 1 \mathbf{nT}^2 \quad (\text{fixed})$$



# Equatorial and Bounce-Averaged PADC



# SUMMARY

1. The Global SC RC Model with Propagating EMIC Waves in the Presence of Heavy Ions has been developed for the first time.
2. It is found that  $\text{He}^+$  -mode energy distributions are not Gaussian distributions, and most important that wave energy can occupy not only the region of generation, i. e. the region of small wave normal angles, but occupies all wave normal angles, including those to near 90 degrees.
3. The latter is extremely crucial for RC precipitation, energy transfer to thermal plasmaspheric electrons by resonant Landau damping, and for the scattering of relativistic electrons from outer RB.
4. An Integrated View of the Inner Magnetosphere and Radiation Belts is Required Global Self-Consistent Coupling Consideration of RC, Plasmasphere, Magnetospheric Electric Field, and EMIC waves.

See poster *Gamayunov et al.*, Tuesday Morning; SM21A-0312.